TEKNILLINEN TIEDEKUNTA

SEPARATION AND TREATMENT METHODS FOR RECYCLED CONCRETE

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ABSTRAKTI

Kierrätysbetonin erotus-ja käsittelymenetelmät

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Työn ohjaajat yliopistolla: Priyadharshini Perumal, Elisa Koivuranta, Mamdouh Omran

Tämän diplomityön tarkoituksena oli identifioida yleisimmät tieteellisessä tutkimuksessa käytettävät kierrätysbetonin täyteaineen käsittelymenetelmät ja toteuttaa useita kokeita kyseisiä menetelmiä hyväksikäyttäen samalta purkutyömaalta hankitulle kierrätysmateriaalille. Työssä käytettyihin käsittelymenetelmiin kuuluivat karbonaatio, mekaaninen hankauskäsittely, mikroaaltokäsittely yhdessä hankauskäsittelyn kanssa, pozzolaanipinnoitus sekä pozzolaanipinnoitus yhdessä karbonaation kanssa.

Työn kokeellinen osuus jakautui kahteen osaan, joissa molemmissa oli omat päämääränsä. Ensimmäisessä osassa tehokkain käsittelymenetelmä määritettiin mittaamalla käsiteltyjen näytteiden tiheyden ja veden absorptiokapasiteetin muutos eri menetelmien välillä, sekä vertaamalla niitä käsittelemättömän kontrollinäytteen arvoihin. Kokeellisen osan toisen vaiheen tavoitteena oli valmistaa betonikappaleita käyttäen täyteaineena ensimmäisen osan näytemateriaaleja ja kvantitatiivisesti määrittää saatujen kappaleiden puristuslujuus ja tutkia SEM-kuvia kyseisistä kappaleista.

Kokeiden tulosten perusteella tehtiin kaksi havaintoa. Ensinnäkin, mekaaninen hankausmenetelmä paransi kierrätetyn täyteaineen fyysisiä ominaisuuksia kaikista tehokkaimmin ja kyseistä menetelmää tulisi tutkia enemmän, etenkin yhdessä karbonaatiomenetelmän kanssa, joka myös antoi lupaavia tuloksia. Toiseksi havaittiin, että betonikuutiot, jotka valmistettiin karbonaatiomenetelmällä ja mekaanisella hankausmenetelmällä käsitellystä täyteaineesta menestyivät parhaiten myös puristuslujuuskokeessa.

Avainsanat: kierrätysbetoni, kiertotalous, karbonaatio, pozzolaanipäällystys, mikroaaltokäsittely, mekaaninen käsittely

ABSTRACT

Separation and treatment methods for recycled concrete

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Supervisors at the university: Priyadharshini Perumal, Elisa Koivuranta, Mamdouh Omran

The main goals of this thesis were to identify most commonly used treatment methods for recycled concrete aggregates (RCA) in scientific research from literature and to perform various types on treatments for recycled concrete aggregates that were procured from the same demolition site. The treatment methods used include CO_2 curing, mechanical abrasion action treatment, microwave treatment combined with abrasion action treatment, pozzolanic coating treatment and pozzolanic coating treatment combined with CO_2 curing.

The experimental part of this thesis consists of two different sections with different goals. In the first part the most effective treatment method is determined by measuring apparent density and water absorption capacity from the treated samples as well as an untreated control sample. The second phase of this thesis was to manufacture concrete from the same treated aggregates and to quantitatively determine compressive strength capacity and to perform SEM imaging for the created concrete specimen.

The first main finding was that mechanical abrasion action treatment increases the RCA:s physical properties most efficiently and it should be studied more, especially in tandem with CO_2 curing, which also yielded promising results. Concrete cubes produced from abrasion action and CO_2 curing samples also performed best in the compressive strength test.

Keywords: recycled concrete, circular economy, carbonation, pozzolanic coating, microwave treatment, mechanical treatment

PREFACE

This Master's thesis was made for the University of Oulu in the Faculty of Technology and department of Fiber and Particle Technology. The main purpose of this thesis was to compare different treatment methods for recycled concrete aggregates and determine the most viable method to enhance the physical properties of recycled concrete.

I want to express my gratitude to my supervisors Priyadharshini Perumal, Elisa Koivuranta and Mamdouh Omran for offering me the opportunity to write this thesis and finding me a suitable topic and their valuable instructions, tutoring and patience throughout the process. Furthermore I want to thank everyone who helped in any way during the experimental work, especially Kalle Kursula, Tommi Kokkonen, Santeri Kaisanlahti and Riitta Kontio as well as everyone from the laboratory staff and Oulu Mining School staff. It has been an honour, a privilege and a valuable experience overall to be a member of the Fiber and Particle Engineering Research Unit.

Last but not least I want to thank Petra Kämäräinen for her endless support, motivation and helpful advice during moments of doubt throughout this process.

Oulu, 14.07.2020

Antti Korva

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SYMBOLS AND ABBREVIATIONS

A	Area
bar	Pressure in bars
°C	Degree in Celsius
$CaCO_3$	Calcium carbonate
$Ca(OH)_2$	Calcium hydroxide
CO_2	Carbon dioxide
cm^3	Cubic centimetre
F	Force
GHz	Gigahertz
g	Gram
H_2O	Water
h	Hours
IDLW	Improved Double Log Washer
ITZ	Interfacial transition zone
kg	Kilogram
kg/m^3	Density
kN/s	Kilonewtons per second
kV	Kilovolt
kV/cm	Electric field strength
kW	Kilowatt
kWh/t	Kilowatt hour per tonne
$Mg(NO_3)_2$	Magnesium nitrate
MPa	Megapascal
m	Mass
m^3	Cubic metre
ml	Millilitre
mm	Millimetre
Na_2SIO_3	Sodium silicate
N	Newton
N_2	Nitrogen
O_2	Oxygen
P	Pressure

RCA	Recycled concrete aggregate
SEM	Scanning electron microscopy
s	Seconds
V	Volume
ρ	Density

1 INTRODUCTION

Environmental issues are the crucial point in decision-making procedures more often than ever before in engineering and industrial applications. Due to huge expansions in industrial activities, rapid emergence of urban areas around the globe among other global phenomena, the production of goods and services has increased exponentially since the latter half of the last century. This has naturally caused the accelerated demand of raw materials to sustain the needs of industrial manufacturing processes. Moreover, the recent economical and industrial growth of countries such as China, India and Brazil will increase the demand of raw materials even further in the near future. (Pepe et. al. 2014, Shi et.al. 2018)

To answer the aforementioned demand of production materials without exhausting Earth's natural resources and producing as limited amount of greenhouse gases as possible at the same time, industrial processes should strive to increase the efficiency of reusing materials. At the same time, these principles will significantly decrease the amount of reusable end products ending up in landfills. (Pepe et. al. 2014)

In Europe, almost 900 million tons of construction and demolition waste is produced annually, in which 20-80% consists of cementitious materials depending on the country of origin. About 60% of extracted new materials is crushed rock and 40% is sand and gravel. This makes concrete the second most consumed material on Earth. Naturally when the demand of concrete increased every year, so does the amount of construction. For example, South Korea reported in 2012 that their domestic construction waste amount was over 186,000 tons per day and it was expected to grow further every year. In Finland, almost 800,000 tons of concrete was recycled and almost 200,000 tons was delivered to a landfill in 2008. Even though all of the used concrete could be recycled for re-use with modern technology, approximately half of the concrete waste ends up in landfill sites. One of the major reasons for the low level of concrete recycling is the inadequate level of concrete strength observed when constructed from recycled materials. (Betoniteollisuus Ry 2010, Menard et. al. 2013, Nam et.al. 2016, Soutsos et.al. 2011)

The reuse of demolished concrete aggregates from demolition waste would greatly contribute to valorise the construction wastes in terms of sustainable development and this is why studies on recycling waste concrete have attracted global interested over the years. However, the application of effective concrete recycling on the field is still very limited. The composition of these waste aggregates also varies significantly and their properties have a substantial influence of the physical properties of the concrete. (Nam et.al. 2016, Spaeth et. al. 2013)

According to the recommendations of The International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM, from the name in French) only 20% of recycled coarse aggregate was allowed to be used for new concrete production while the recycled fine aggregate was not recommended to be used for structural concrete production at all. This is why enhancing the properties of recycled aggregates with different kinds of treatment methods is essential to extend the application range of said aggregates. (Shi et.al. 2018, Zhan et. al. 2014)

The goal of this thesis was to identify most commonly used treatment methods for recycled concrete aggregates in scientific research and to perform various types on treatments for recycled concrete aggregates that were procured from the same demolition site and to determine the most effective treatment method by measuring various parameters from the treated samples as well as an untreated control sample. The final phase of this thesis was to manufacture concrete from the same treated aggregates and to quantitatively determine the most important physical properties of the created concrete specimen. The final chapter of this thesis contains the conclusions of the aforementioned experiments and discussion about the most viable treatment method for industrial level use in the future.

2 RECYCLED CONCRETE

2.1 Recycled concrete aggregate

Concrete is a composite material that consists of two phases: the cement paste (22%) and aggregates (78%). The aggregate phase of concrete in turn consists of natural sand and different kinds of gravel and about 5% of the total composition is water. A chart depicting the composition of concrete mix is presented in Figure 1.

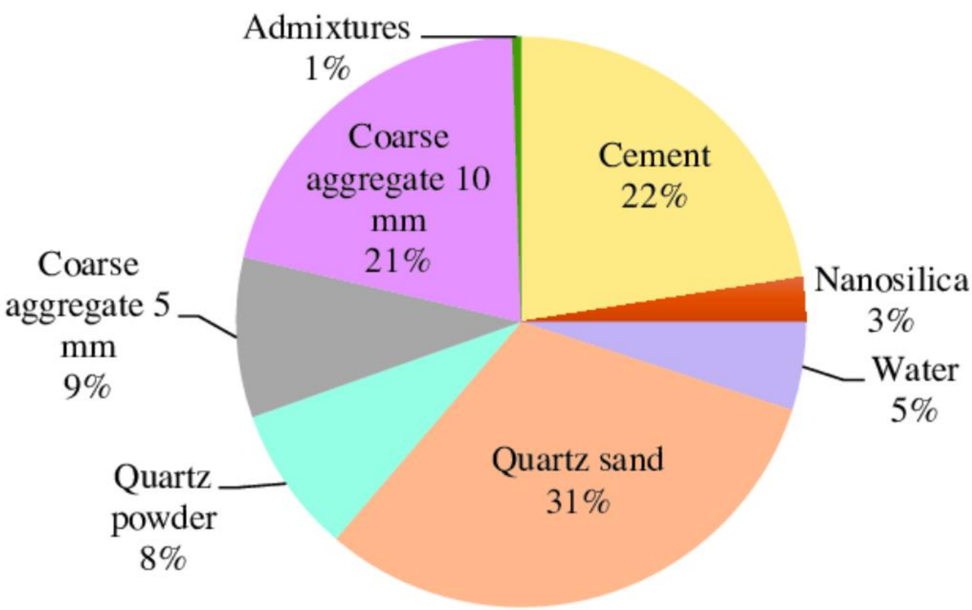


Figure 1. Composition of concrete mix

To overcome the strength issues of recycled concrete, many different separation and treatment methods can be used to remove mortar material from the used concrete material and separate the cement and aggregate phases from each other as effectively as possible. (Menard et. al. 2013, Nasution et. al. 2015)

The presence of adhered mortar in the recycled concrete aggregates results in lower density, greater water absorption and inferior mechanical strength compared to natural aggregates. The properties of concrete manufactured with recycled aggregates can be improved by mixing several kinds of mineral additives with the recycled components. For example, these mineral additives include rice husk-bark ash, fly ash and silica fume, granulated blast slag and metakaolin. One experimental result confirms that the compressive strength of recycled concrete aggregate does increase with these changes to the mix proportioning or the mix process of the material. However, aforementioned methods do not improve the properties of the recycled aggregate itself. (Zhan et. al. 2014)

2.2 Treatment methods

2.2.1 The aim of treatments

The treatment methods to enhance the properties of recycled concrete aggregates can be divided into two categories. The more common and obvious way to increase the compressive strength is to remove or reduce the amount of mortar and other impurities from the recycled material. Similar results can also be achieved by keeping the amount of mortar intact in the material and enhancing the properties of the concrete by strengthening the mortar itself by manipulating its physical structure. (Liang et.al. 2020, Zhan et. al. 2014)

The most commonly studied and used treatment methods for recycled concrete aggregates are introduced in the following chapters along with some of the results that have been achieved with the particular methods in recent studies. All of the following treatments presented have currently been utilised mainly in laboratory-level experiments.

2.2.2 CO_2 curing

The goal of CO_2 curing, or carbonation treatment, is to enhance the mechanical properties of adhered mortar on the surface of the recycled concrete aggregates by increasing its solid volume by decreasing porosity and decreasing the water absorption capacity of the RCA (recycled concrete aggregate). This is achieved by a chemical reaction between CO_2 and calcium hydroxide, which is one of the main cement hydration products on the surface of the recycled concrete aggregates. The reaction is presented in formula 1.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \tag{1}$$

Where $Ca(OH)_2$ is calcium hydroxide and $CaCO_3$ is calcium carbonate.

The other hydration products, such as calcium silicate hydrate have been determined to also partially convert into calcium carbonate, which increases the solid volume of the recycled aggregates further and decreases porosity. The moisture content of the treated recycled concrete aggregates also influences the achieved carbonation percentage, since material with low moisture content limits the carbonation reactions and a saturated material has pores that are filled with water thus limiting the CO_2 penetration of the treatment. It has also been determined that recycled concrete aggregate with smaller particle sizes are easier to carbonate due to the larger reaction surface area. (Shi et.al. 2018, Zhan et.al. 2014)

Accelerated carbonation is achieved by increasing the carbon dioxide concentration and relative humidity and temperature. The carbonation processing time is also an important factor of the treatment, but it has been determined that the carbonation proceeds rapidly for the first two hours of the treatment and then slows down significantly after that. An example of carbonation percentage of RCA versus carbonation curing time is presented in Figure 2. (Liang et. al. 2020, Zhan et.al. 2014)

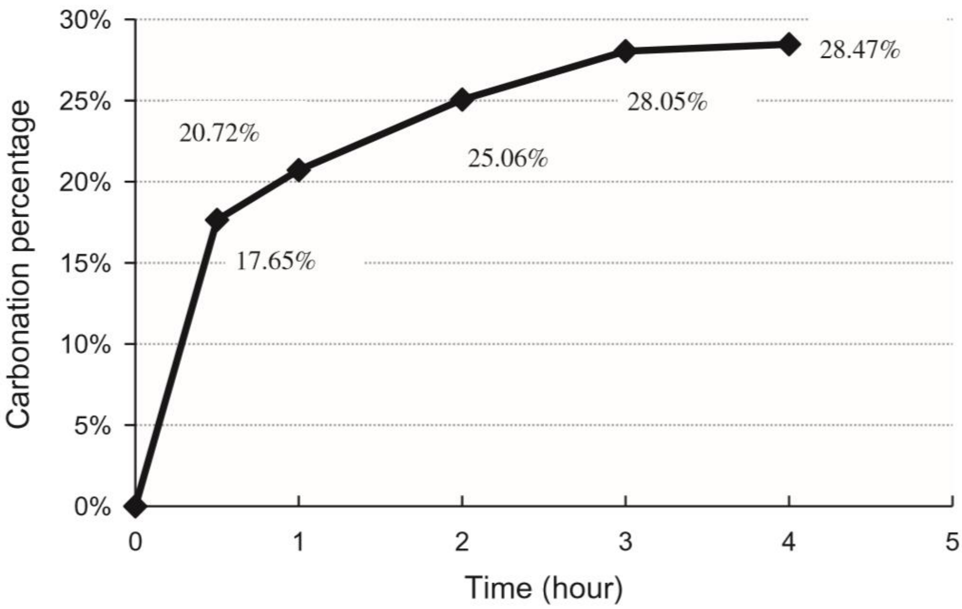


Figure 2. Carbonation percentage of RCA versus carbonation curing time (Liang et.al. 2020)

In the standard carbonation method recycled aggregate is placed in a carbonation chamber working in a temperature of around 20°C, relative humidity of around 70% and CO_2 concentration of around 20%. Due to ambient pressure the penetration rate of CO_2 into recycled aggregate was low and the duration time should be prolonged. The required equipment for standard carbonation is fairly simple as it only requires a carbonation chamber, controller sensors and a carbon dioxide tank. (Liang et. al. 2020, Shi et.al. 2018)

When performing treatments using the pressurized carbonation method a similar carbonation chamber is used, but the processing temperature is a bit higher (around 25°C) and the relative humidity is lower (around 50%). In addition a vacuum pump is used to reduce the air pressure in the chamber to -0,6bar and CO_2 pressure is controlled by a gas regulator. Carbonation efficiency is much higher compared to standard carbonisation. The necessary equipment is similar to the standard carbonation method, but in addition a vacuum pump and regulators for the chamber and the carbon dioxide cylinder are required. (Liang et. al. 2020, Shi et.al. 2018)

Flow-through CO_2 curing method is performed by using a mixture of air gas and CO_2 gas (10% concentration) that is injected to the mesh container from one side of the chamber and ejected from the other. Relative humidity of the chamber is maintained around 50% by using a saturated $Mg(NO_3)_2$ solution. This method had lower energy consumption and higher carbonation efficiency than the standard carbonation method. (Shi et.al. 2018, Zhan et.al. 2014)

The fourth commonly used CO_2 curing method is the water-CO_2 cooperative curing method, in which the recycled aggregate samples are inserted into a vessel containing water and mixtures of CO_2, O_2 and N_2 gases are injected into the water. The CO_2 nano-bubbles could also be mixed with the water to further enhance the carbonation efficiency. This method was deemed appropriate for recycled fine aggregate and recycled powder. The required equipment is therefore fairly minimal, since only the necessary gas cylinders and the water-filled reaction vessel are the only needed equipment. (Liang et. al. 2020)

The effect on the compressive strength of the treated aggregates have been found to have a close linear relationship with the observed carbonation depth regardless of the duration of the CO_2 curing. The depth of the carbonation is affected by the mortar strength of the treated material. (Shi et.al. 2018)

It has also been determined that natural carbonation can reduce the alkalinity of concrete, which in turn may lead to corrosion of steel reinforcement in reinforced concrete structures. This can have an impact on the lifetime of reinforced structures made with concrete that has been treated with carbonation. (Shi et.al. 2018)

2.2.3 Polymer treatments

The main goal of polymer treatments are usually to enhance the fragmentation resistance and to lower the water absorption capacity of the recycled concrete aggregates. These sorts of treatments tend to emphasize the formation of a polymeric film in the pores of the RCA which has been determined to significantly reduce the water absorption capacity of the recycled concrete aggregates. This sort of polymeric film has also been determined to be very resistant in alkali environments, which in turn enhances the properties of recycled concrete used in steel reinforced structures. (Makul 2020, Spaeth et.al. 2013)

The properties of recycled concrete aggregates can be improved by impregnation of polymers. The measured parameters were water absorption, fragmentation resistance and microstructure of RCA and comparing them with the properties of natural aggregates. Different polymer solutions are prepared with different concentrations in laboratory conditions. Then, recycled concrete aggregates containing various levels of fineness are soaked in said polymer solutions. The optimal concentration and combination of used polymer solution to improve the properties of RCA are determined. The aggregate samples are dried in a 110°C oven for 24-48 hours before impregnation procedure. Impregnation can be achieved with two different methods. In the method called "combination with single impregnation" the aggregate samples are impregnated by six types of polymer solutions for five minutes each, then dried at temperature of 20°C and relative humidity of around 50% for 24 hours. After that the samples are further dried in a ventilated oven (temperature of 50%) for another 24 hours. On the other hand, in a method called "combination with double impregnation and heat treatment" the aggregate samples are impregnated in soluble sodium silicate solution (polymer solution 1) for 3 minutes followed by drying for 20 hours in room temperature. After that, the samples are impregnated for 5 minutes each with the remaining five different polymer solutions and then followed by similar drying process as with combination with single impregnation process. (Spaeth et. al. 2013)

Polyvinyl alcohol treatment is also a viable treatment to enhance the compressive and flexural strengths of recycled concrete aggregates due to the properties of polyvinyl alcohol itself: it has a high modulus of elasticity and tensile strength and its solubility to water reduces the setting time and enhances its adhesiveness, which in turn makes it easier to penetrate into the pores of the recycled concrete aggregates. The polyvinyl alcohol treatment can be performed via injection, coating and vacuum impregnation. The treatment process can also include a section where the RCA is immersed into a polyvinyl alcohol solution for a set amount of time. The polyvinyl alcohol treatment method has also been demonstrated to reduce the number of cracks present in the recycled aggregates. The polyvinyl alcohol fiber has been determined not to have a harmful impact on the environment, since it does not produce any hazardous waste. Despite this, the whole process of polyvinyl alcohol treatment itself produces a notable amount of waste. The costs of the process are also considerable due to the expensive materials needed for the treatment. (Makul 2020, Nam et.al. 2016)

2.2.4 Hybrid treatment methods

The hybrid method used in this experiment consists of a chemical process followed by a mechanical process. The aim of the chemical process is to soften or remove the adhesion mortar from the aggregate samples and the goal of the mechanical process is to remove the residual or softened mortar altogether. The recycled aggregates go through a washing process before treatment to minimize the amount of impurities within the sample. The first phase of the three-stage hybrid treatment is the washing procedure: the recycled aggregates go through a repeated washing process to minimize the amount of fine powders, adhered mortar and multitude of impurities (for example paper, wood, asphalt, glass, plastic, construction debris etc.) to increase the mechanical properties and decrease the water absorption rate of the recycled aggregates. The second phase is called acid-dipping in which the recycled aggregate samples are dipped in an aqueous solution of sulfuric acid and hydrochloric acid with a ratio of 1:11 between acid and water. The samples are immersed in the water-acid solution for 24 hours to allow sufficient reaction. The third and final phase is the active mechanical treatment, which can be done with various different mechanical treatment methods. One method which Song et.al. (2014) used in their research was divided into two separate phases and used very specific and advanced machinery. At first the crushed recycle aggregates are processed in an Improved Double Log Washer (IDLW). The immersed aggregate mass is loaded into the lower part of the IDLW which leads to the separation of impurities and mortar by impact force and friction created by the rotating paddles of the IDLW. Lastly, the separated impurities and mortar are removed through the axial lower part of the IDLW and the high quality recycled aggregates are conveyed to the upper part of the IDLW. The same procedure can also be done with different equipment and mechanical treatment methods as long as the treatment is successful in effectively separating impurities from the treated material. (Song et. al. 2014)

2.2.5 Mechanical treatment methods

Mechanical treatment approaches have been determined to have various advantages that make them relatively feasible for improving the physical properties of recycled concrete aggregates. Mechanical treatment methods are usually used as complementary treatment methods for other treatment techniques, such as microwave treatment, where the goal is to remove the old adhered mortar from the surface of the treated material. Despite this, mechanical treatments can be used by themselves to enhance the properties of RCAs. A good example of a standalone mechanical treatment method is the mechanical abrasion action technique, which effectively reduces the amount of adhered mortar on the surface of recycled concrete aggregates and thus improves the compressive and flexural strengths of the treated material. Abrasion action mechanical treatment can be performed with different types of equipment, as long as the surfaces of the treated aggregates effectively rub against either each other, or the surface of the treatment equipment. (Makul 2020)

One specific method of mechanical treatment of recycled concrete aggregates that has been studied recently is a three phased mechanical treatment protocol. The recycled concrete aggregates are treated in three distinct process stages to minimize the amount of impurities and decrease the amount of attached mortar as much as possible from the aggregate surfaces. The first stage of the treatment is called particle homogenisation, in which the objective is to homogenise the demolition debris and remove residual impurities (wood, metals and plastic pieces). At first, the debris is divided into two fractions based on their dominant colour: grey and red. After that, the raw materials are distributed on a plastic sheet in different layers to form “cells” of homogenous particles. The second stage of the treatment is grinding and sieving, where the goal is to transform the debris into aggregates of the wanted particle size. At first the homogenous materials are grinded with a jaw crusher (model Queixada 200 produced by Vegedry) and during the grinding the material is divided into coarse and fine aggregates. For each sample of the homogenised material about 60% was defined as fine aggregates. After grinding, the recycled aggregates are sieved and divided into three size classes based on their nominal diameter. The third and final stage of the treatment is autogenous cleaning, where the aim is to remove as much mortar from the aggregate surfaces as possible. To achieve this, the recycled aggregates are placed in a rotating mill drum to collide with each other. The drum is filled with about 33% of its volume with recycled aggregates. Different processing times were tested varying from minimum processing time of 2 minutes to the maximum processing time of 15 minutes. After the autogenous cleaning process the aggregates are finally washed with water and dried. The results reported that autogenous cleaning implemented at the laboratory scale enhanced the properties of recycled concrete aggregates, especially the reduced amount of mortar on the surfaces of the aggregates and their water absorption capacity. (Pepe et. al. 2014)

For successful mechanical beneficiation two techniques have been proposed in Japan: eccentric shaft rotor and mechanical grinding. In the eccentric-shaft rotor method, concrete lumps are passed downward between outer and inner cylinders that rotate at high speed to separate the coarse aggregate from the mortar through grinding. In the mechanical grinding method the grinding drum is divided into small sections with partitions and the mortar is removed from the aggregate by rubbing against iron balls placed in each section of the drum. (Akbarnezhad et. al. 2011)

2.2.6 Microwave-assisted treatment

Microwave-assisted beneficiation is based on the difference in heating rate (or microwave energy absorption rate) between mortar and aggregates. Since mortar absorbs heat more effectively than aggregates and also has higher water absorption rate, it is under more thermal stress and becomes brittle during the process. In a Singaporean study this method was tested using a pilot industrial-degree microwave oven that could be operated continuously at a power level of 10kW. The equipment consisted of the microwave generator unit and a recycled concrete aggregate heating chamber with ventilation to remove dust and water vapour during the heating process. In addition the system included various waveguide components to protect the machinery from reflected power. (Akbarnezhad et. al. 2011)

In the experiments the system was used to heat up recycled concrete aggregate samples weighing 2kg and heating them at maximum power (10kW) for 1 minute. After the heating process the samples were instantly immersed in 25°C water and then dried in room temperature for 21 days. (Akbarnezhad et. al. 2011)

2.2.7 High voltage assisted beneficiation

The high voltage assisted beneficiation method is based on the use of pulses of high voltage electricity (a few kV/cm) through recycled aggregate samples that are immersed in water. The goal of the method is to cause selective fragmentation between the aggregate material and mortar material. (Menard et. al. 2013)

This technique is operated by using two electrodes in a water-filled container in which the high voltage pulsed are conducted. Electronic fragmentation causes a shock wave front in the water, which in turn selectively fragments the mortar material in the samples. When the predetermined voltage is reached, the energy of the pulse generator through the solid sample to the counter electrode of the process container. This cycle of charging and discharging continues until the selected number of high voltage pulses have been reached. The referred experiment was conducted with a selFrag Lab machine (manufactured by selFrag AG) and the size distribution of used test samples were between 0.4-31.5mm in diameter, with the mass of one test sample being about one kilogram. The adjustable test settings included parameters such as pulse frequency, total number of pulses, discharge voltage (energy per pulse) and electrode gap of discharge. Additional tests made with recycled concrete revealed that the high voltage assisted beneficiation method remained efficient for concrete fragmentation with different cementitious compositions and other characteristics. The energy consumption of the process was also verified to be relatively low, being less than <3kWh/t. (Menard et. al. 2013)

2.2.8 Pozzolanic coating

The goal of pozzolanic coating treatments is to increase the workability and higher compressive and flexular strength of recycled concrete aggregates. Also theoretically the chemical reinforcement methods such as pozzolanic coating can be expected to reduce porosity of recycled aggregate materials and so improve the interfacial bond between the RCA particles and new cement mortar. The treatment will also slightly increase the apparent density of recycled concrete aggregates. The higher strength properties are achieved by enveloping crushed RCA particles with a pozzolanic slurry which contents may vastly vary. Most commonly used coating materials include components such as fly ash, silica fume, blast furnace slag or a blended mixture of mentioned components. It has been determined that the materials used in the slurry will have an effect on the fluidity of the concrete made with aggregates coated with a pozzolanic slurry. (Li et.al. 2009,Shi et.al. 2018, Zhao et.al. 2013)

In addition to the mineral components mentioned above, a liquid component is always included in pozzolanic coating treatments. The most commonly used liquid component is water, but chemical solutions such as sodium silicate (Na_2SiO_3) are also used. The proportion of liquid component compared to the amount of mineral components in the coating paste have a significant impact on the crushing strength of the recycled aggregate material. In a study conducted by Zhao et.al in 2013 it was determined that a water to cement ratio of 0.8 resulted in the highest physical performance, which indicated that too much or too little coating paste leads to reduced crushing strength properties of recycled concrete aggregates. (Li et. al. 2009, Zhao et. al. 2013)

A study performed by Shi et.al. (2018) resulted in an observation that combining pozzolanic coating treatment with carbonation treatment was an effective method to reduce water absorption and enhance mechanical strength. On the other hand, the results also exhibited that CO_2 treatment was effective for enhancing the fluidity of the concrete whereas the pozzolanic coating treatment was found to decrease fluidity. (Shi et.al. 2018)

2.2.9 Thermal treatment methods and other applications

The aim of this method is to make the mortar present in the aggregates more brittle via dehydration. In thermal beneficiation treatment the recycled concrete aggregates are heated for approximately two hours in a temperature of 500°C. To further enhance the effect of the mortar removal, the heated aggregates can be submerged in cold water immediately after heating. (Akbarnezhad et. al. 2011)

Thermal-mechanical beneficiation is basically the combination of the two previously mentioned methods. The recycled aggregates are first heated in a vertical furnace in a temperature of 300-500°C to make the aggregate brittle via dehydration. After that the heated aggregate is fed to the rubbing equipment (grinding drum or shaft) to remove the dehydrated mortar. The separated mortar is then screened from the aggregate and discharged. (Akbarnezhad et. al. 2011)

Chemical-Mechanical beneficiation method consists of two phases: introducing chemical degradation through exposure of recycled concrete aggregates to sodium sulfate solution and mechanical stress created with freeze-and thaw action to separate mortar from the concrete aggregates. (Akbarnezhad et. al. 2011)

2.4 Utilisation possibilities of recycled concrete aggregates

2.4.1 Highway pavements and pavement blocks

The construction of highway pavements consumes enormous amounts of natural resources and they are very expensive infrastructures to build. The usage of recycled concrete aggregates for construction of highway pavements would result in an extensive conservation of natural resources and massive reduction of harmful gas emissions compared to the usage of natural aggregates. It would also help to reduce the carbon footprint and economic costs of the pavement construction industry. The use of recycled concrete in construction would be especially beneficial in large cities and other highly urban areas where regeneration of materials would be a viable solutions due to ongoing infrastructure replacement. (Nwakaire et.al. 2020, Soutsos et.al. 2011)

Even though the mechanical and physical properties of recycled concrete aggregates are inferior compared to natural aggregates, most of the desired properties of RCA are still satisfactory except for water absorption capacity. Therefore recycled concrete aggregates would still need to be treated to reduce the water absorption capacity so it can totally utilised in highway pavement construction. Recycled demolition aggregates can also be used in construction of concrete pavement blocks to replace newly produced limestone aggregates if the size range of the aggregates can be adjusted optimally. Unlike highway pavements or other surfaces, the supply of input materials and storage of output materials are relatively easy to manage, which helps to make the usage of recycled materials cost efficient. (Nwakaire et.al. 2020, Soutsos et.al. 2011)

Total utilisation of RCA for rigid pavement surfaces can be achieved, especially for the lower layers of pavement, but some precautionary need to be taken to minimise the negative effects. It has also been determined that recycled concrete aggregates can be used for flexible pavement construction, but the composition of the asphalt mix need to be changed, as they can require higher amounts of binder agents. Better results can also be achieved by increasing the thickness of the pavement layer, but this naturally increases the costs of construction. The utilisation of recycled concrete aggregates for highway pavement construction should be encouraged after more research data on the topic has been produced and standard specifications and guidelines have been established. (Nwakaire et.al. 2020)

2.4.2 Buildings made with recycled concrete

Actual buildings made solely of recycled concrete are still very rare due to the challenges of cost-effectively manufacturing large amounts of recycled concrete at building sites or their immediate vicinity.

Despite this, a concrete supplier company Fibo Intercon helped build one of the first buildings out of recycled concrete for Pelican Self Storage in Denmark in 2019. The purpose of the project was to solely re-use crushed concrete from an existing building and use the aggregate material for the concrete elements of the new Pelican Self Storage warehouse. The demolition material was sorted and crushed on site and during the design process they casted test cubes to ensure the recycled concrete met their strength property criteria. The moisture content of the aggregates was also monitored using a computer software built into the concrete batching plant. (Fibo Intercon 2019)

The project was successful and it had numerous benefits, including reduced cost of purchasing quarried aggregates, lower transport costs and reduced CO_2 emissions due to reduced transport of materials. (Fibo Intercon 2019)

It should be noted that this information was taken directly from the company website of Fibo Intercon and the article is meant to advertise the accomplishments of the company. The article also did not contain any in-depth information about their materials or treatment methods.

3 MATERIALS AND METHODS

3.1 Materials

3.1.1 Separation

The sample material for the experiments of this thesis was procured from Purkupiha Group and the material originates from Finnish building demolition sites. All of the sample material used in this thesis is from the same building demolition site and thus its composition is similar across all samples.

The first phase of the sample preparation was to separate the usable recycled concrete from other materials. Since the material originated from a building demolition site, it contained a lot impurities including various types of stone, pieces of metal, sand, plastic and electrical wires. An example of the material before separation is shown in Figure 3. The separation was done by hand and approximately 75-80% of the materials were discarded due to being unusable in the experiments.

Figure 3. Sample material before separation

After separating the usable recycled concrete material from the material was washed with water to remove any residual sand and other impurities. The separated concrete material is shown in Figure 4.

Figure 4. Sample material after separation

After the usable sample material was separated, it was dried in a 100°C oven for 24 hours to remove as much moisture from the material as possible. After the drying procedure the sample material was ready for mechanical crushing.

3.1.2 Mechanical crushing

Before the sample material could be used in treatment experiments it had to be crushed into smaller particle size. The desirable particle size for this experiment was defined to be in the range of 2-16mm size in diameter.

The crushing was performed with a jaw crusher manufactured by Metso and the procedure took place in the Oulu mining school pilot-factory facilities, which is located in the University of Oulu. A picture of the Metso jaw crusher is shown in Figure 5.

The only adjustable parameter of the jaw crusher that was significant in performing the crushing was the width of the crushing jaws, which dictates the size distribution of the crushed end product. The width of the jaws was set to 8mm, in which case most of the crushed product should be in the 4-15mm size range in diameter. However, the material had to be fed into the crusher up to 25-30 times before it was crushed properly to the desired particle size.

After the crushing process was completed the crushed material was sieved through 2mm and 16mm sieves. The fine material that passed the 2mm sieve was stored in a separate container and the oversized material that did not pass the 16mm sieve was fed to the jaw crusher again several times until it was crushed to the appropriate size.

Figure 5. Jaw crusher used in mechanical crushing

After the material was crushed and sieved to match the desired particle size distribution it was ready for the following physical property measurements. A picture of the crushed and sieved sample material is shown in Figure 6.

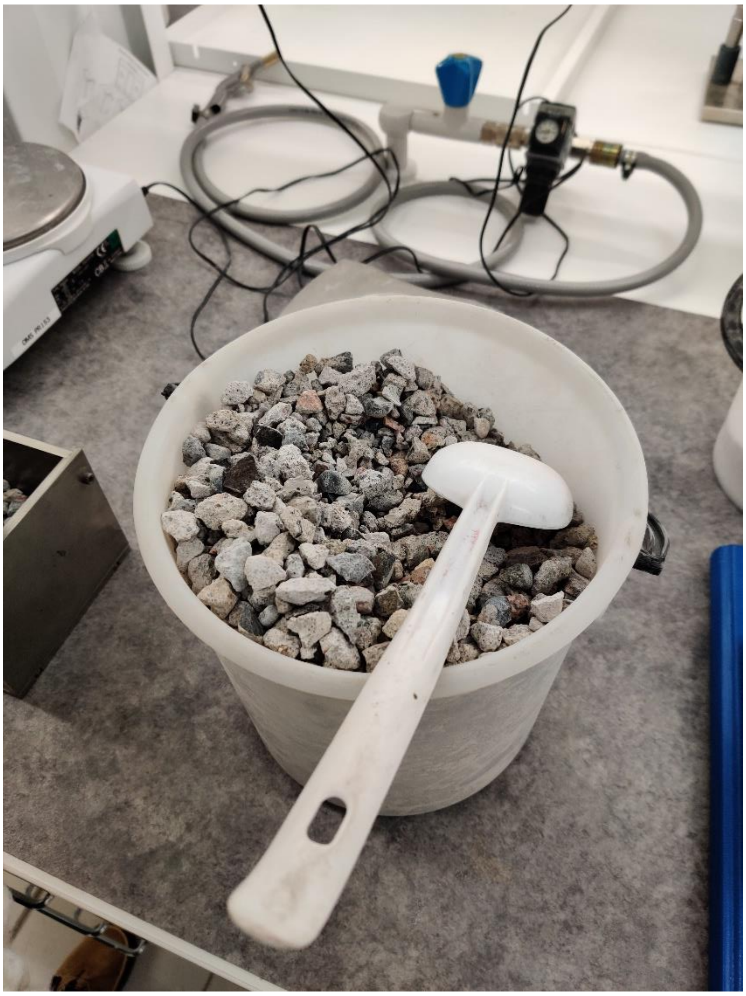


Figure 6. Sample material after mechanical crushing

3.2 Methodology

3.2.1 Recycled concrete aggregate properties

Before applying any of the treatment methods mentioned in the previous chapter there are various parameters that should be defined from the RCA samples to measure the efficiency of used treatment method. Many of the properties are common for all of the selected treatment methods. The measureable properties for their corresponding treatment methods are presented in Table 1.

Table 1. Key RCA properties for different treatment methods.

Treatment method:	Properties:
CO_2 curing	Density, water absorption, mortar strength, crushing value, porosity, particle size
Microwave treatment	Density, water absorption, particle size, composition
Pozzolanic coating	Density, water absorption, particle size, porosity, crushing value
Abrasive action	Density, water absorption, particle size, porosity, crushing value

When performing carbon dioxide curing for the RCA samples, the following properties should be known beforehand: apparent density (kg/m^3), water absorption (%), mortar strength (MPa), particle size (mm), crushing value and porosity (%).

During and after testing, the most important parameters to measure are temperature, relative humidity and the effect of the treatment with different time spans.

Moisture content and theoretical mass gain ratio, which mainly consists of accumulated water mass, can also be measured after the CO2 treatment.

When performing microwave assisted treatment for the RCA samples, the following properties should be known beforehand: composition (total mortar content, amount of natural sand, amount of cement etc.), particle size (mm), water absorption (%) and apparent density (kg/m^3). Additionally, the volume of the test batch directly affects the degree of microwave heating efficiency and the resulted temperature so the test batches should be small enough (2kg or less) to accurately measure the efficiency of the treatment method.

The power of the microwave also affects the effectiveness of the microwave treatment, since by increasing the power intensity of the microwave (kW) larger batches of concrete can be treated at once. To measure the remaining mortar content in the samples after treatment can be achieved by comparing the weights of the pre-treatment, oven dried samples and the treated, sieved samples. The difference between the measurements gives the approximate amount of separated mortar mass.

Before any actual treatment method experiments could be performed, the apparent density and water absorption capacity of the samples had to be measured first. Before performing any measurements though the crushed sample material was dried in a 100°C oven for 24 hours. Properties of the untreated recycled concrete aggregate are presented in Table 2.

Table 2. Properties of untreated recycled concrete aggregate.

Density (kg/m^3)	Water absorption (%)	Particle size range (mm)
1160	7.96	2-12

3.2.1.1 Density

The density of a substance is its mass per unit volume and its commonly used SI unit is kg/m^3. The equation for calculating the density of a substance is presented as formula 2.

$$\rho = \frac{m}{V} \tag{2}$$

Where ρ is the density, m is the mass (kg) and V is the volume (m^3) of the substance.

The first time a density measurement was performed, a $0.001m^3$ metal cube was used as a vessel for the sample material. However, since the future samples for treatment experiments were significantly smaller in volume, a 600ml plastic container was used instead in the following density measurements.

Initial density measurements resulted in the samples apparent density being $1160kg/m^3$. One of the goals of the treatment methods is to increase the density of the recycled concrete to enhance its compression strength and other related attributes.

3.2.1.2 Water absorption capacity

Water absorption capacity is by definition the maximum amount of water a substance can absorb without becoming saturated. To measure the water absorption capacity of the recycled concrete samples, following steps were made. Firstly, 500g of dried sample material was measured into a metallic container. After that, the sample was submerged underwater for 24 hours. After draining the sample of excess water the surface of the material was also dried to remove any residual water from the sample. Finally, the sample was put into a new and dry metallic container and its mass was measured again with a scale. A picture of the preparation of the sample is shown in Figure 7.

The water absorption capacity of the recycled concrete aggregate sample was calculated with the equation presented in formula 3.

$$Water\ absorption = \frac{wet\ weight - dry\ weight}{dry\ weight} \times 100\% \qquad (3)$$

Where *dry weight* represents the samples dry mass and *wet weight* represents the samples mass after the 24 hour water immersion and subsequent draining and wiping. The equation is then multiplied hundredfold to get the value in percentages. One of the goals of the treatment methods is to minimise the amount of water the material absorbs to enhance its physical attributes.

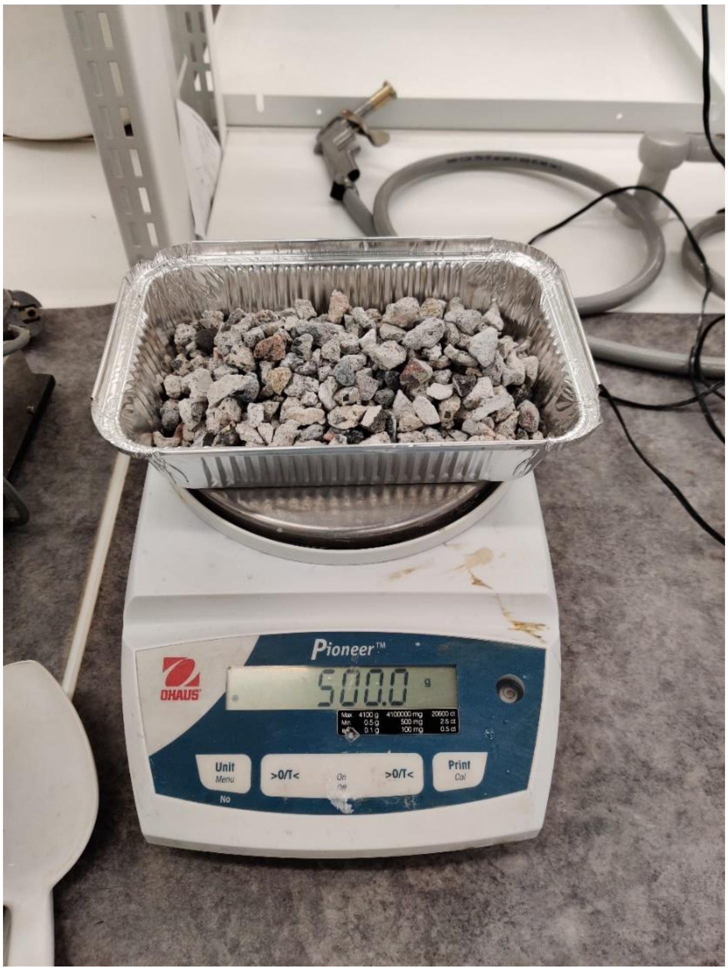


Figure 7. Sample preparation for water absorption measurements

A picture showing a variety of samples immersed underwater for water absorption capacity measurements is presented in Figure 8.

Figure 8. Samples immersed underwater for water absorption capacity measurements.

3.2.2 Treatment methods

3.2.2.1 Carbon dioxide curing

3.2.2.1.1 Pre-treatment preparations

As during the water absorption capacity measurements, a dried sample was measured into a metallic container (as shown in Figure 5). As the sample material was taken from the same material reserve as the previous samples, its apparent density is approximately the same as the density previously measured (1160kg/m^3).

3.2.2.1.2 Carbonation

The standard carbonation method was used for this experiment due to the lack of necessary equipment for any other variation of CO_2 curing. The sample was placed in a carbonation chamber for a set amount of time and then removed as that time had passed. The process circumstances inside the carbonation chamber are shown in Table 3.

Table 3. Carbonation chamber process circumstances

Property	Value
Processing time (h)	24
Temperature (°C)	20
Humidity (%)	60
CO_2 concentration (%)	10

A photo of the carbonation chamber used in the experiments is presented in Figure 9.

Figure 9. Carbonation chamber

3.2.2.2 Microwave treatment

3.2.2.2.1 Sample preparation

For the microwave assisted beneficiation experiment two samples were prepared instead of only one. The samples were taken from the same reserve with identical composition. The only difference between the samples was in their moisture content, since one of the samples had been submerged underwater for 24 hours before testing and the other one was dried in a 100°C oven for 24 hours before testing. A picture of a sample before it was put into the microwave is presented in Figure 10.

Figure 10. A microwave beneficiation sample before treatment

3.2.2.2.1 Microwave specifications

The microwave used in the experiment was a Chinese microwave oven manufactured by the Key Laboratory of Unconventional Metallurgy in Kunming University of Science and Technology, China. The microwave was adjusted to operate for 600 seconds for this particular experiment. The power supply of the microwave was four magnetrons that operated with a power of 4kW and a frequency of 2.45GHz. The microwave was cooled using a water circulation system. A photograph of the microwave used in the experiment is presented in Figure 11.

Figure 11. Microwave oven used in the experiment

The samples were treated separately, since the oven included only one temperature sensor (thermal rod) that is pushed about 2cm deep into the sample for the duration of the experiment. The samples themselves were put into an alumina crucible (diameter 8cm, height 10cm) that in turn was covered by alumina layer to ensure efficient heating, and lastly with a layer of Styrofoam complimented with a lid of the same material. The crucible was positioned at the center of the microwave radiation.

The sample was treated in the microwave oven for 600 seconds and its temperature was measured throughout the heating process with a thermocouple. The sample was kept inside the oven for additional 130 seconds to get a more accurate reading on the maximum temperature. Finally, the samples mass was measured after letting the sample cool down near to room temperature.

After cooling and weighing the microwave sample it was mechanically treated with an empty barmill manufactured by Wedag to remove adhered mortar from the surface of the aggregates without powdering the sample material. The sample was treated for 300 seconds and was immediately sieved through a 2mm sieve to remove powdered material.

3.2.2.3 Abrasive action

Abrasive action treatment is a form of mechanical treatment where the goal is to remove excess mortar from the surface of the recycled aggregate material. The mortar is removed mechanically by forcing the aggregate particles rub against each other and the surface of the milling equipment.

3.2.3.3.1 Equipment

The abrasive action treatment was performed with a small bar mill manufactured by Wedag. To avoid any unnecessary crushing and powdering of the sample material, no crushing rods were used during the experiment and so the mill was used with only the sample aggregate material inside.

The Wedag-mills operating speed was set to 1rpm and the processing time was determined to be 300 seconds of uninterrupted milling followed by sieving the material through a 2mm sieve to remove the fine powdered material. A photo of the Wedag-mill is presented in Figure 12.

Figure 12. Wedag-mill used in the abrasive action treatment

3.2.2.4 Pozzolanic coating

Two 500g samples of recycled concrete aggregate were prepared for this treatment and the goal of the experiment was to mix the aggregate in a slag-water solution with different proportions. The proportions used in the experiment are presented in Table 4.

Table 4. Mixing proportions of the pozzolanic coating samples.

Mix number	RCA (g)	Slag (g)	Water (ml)
Mix 1	500	200	400
Mix 2	500	300	300

After measuring the RCA-samples and the components of the coating slurries the dry materials were mixed in a Kenwood-mixer for about 30 seconds before adding the water component. After introducing the liquid component into the mix, the slurry was mixed for approximately 60 seconds before pouring it into a tray. After pouring the sample was allowed to rest in room temperature for 24 hours. A photo of the samples after mixing is presented in Figure 13.

After the samples had been allowed to rest for 24 hours, each sample was drained of excess liquid and divided into two smaller samples based on their mass. After division half of the sample was sealed in a plastic bag for six days and the other half was treated in a carbonation chamber for 24 hours in identical circumstances as with the CO_2-treated sample introduced in chapter 3.2.2.1. After the carbonation chamber treatment the sample was also sealed in a plastic bag for five days.

Figure 13. Pozzolanic coating samples after mixing.

Seven days after the initial mixing the sample material with the pozzolanic coating slurry the samples were dried in a 100°C oven for 24 hours. After this the samples were sieved through a 2mm sieve to remove any excess powder that can be assumed to be mainly consisted of dried coating slurry. After sieving the samples were weighed to determine the dry weight of the samples for water absorption testing. As the dry mass of the samples was measured they were afterwards immersed underwater for 24 hours. After removing the excess water and wiping the surfaces of the sample materials the wet weight of the samples could be measured and the water absorption capacities could be calculated.

4 RESULTS AND DISCUSSION

4.1 Recycled concrete aggregate

4.1.1 Carbonation

4.1.1.1 Density

After the sample was removed from the carbonation chamber it was time to measure its density again to see if the CO_2 treatment had increased the apparent density of the sample. Following the same steps as previously explained, the density was calculated using formula 1 and resulted in the apparent density of the sample being 1202.3kg/m^3, or 3.6% higher than the density of an untreated sample.

4.1.1.2 Water absorption capacity

Similarly to the density testing, a new value for water absorption capacity needed to be defined after the carbonation treatment to see if the treatment had reduced the materials capability of absorbing moisture.

Following the same steps as explained in 2.3.2, the sample was first submerged underwater for 24 hours before it was drained and wiped and finally its mass was measured to define the samples *wet weight.* Afterwards the sample was dried for another 24 hours in a 100°C oven and then its mass was measured again to define the samples *dry weight.*

Finally, the new H_2O absorption rate could be calculated using formula 2 and resulted in the value of 7.87% or 0.09% lower than the value for an untreated sample. The difference between a treated sample and an untreated sample is very marginal, and this indicates that a longer curing time, as with the research of Liang et.al. (2020), is needed to substantially decrease the water absorption capacity of RCA.

The differences in important testing parameters between an untreated sample and a CO_2 treated sample are presented in Table 5.

Table 5. Differences between and untreated sample and a CO_2 treated sample.

Property	Untreated sample	CO_2 treated sample
sample mass (g)	500.0	500.0 (before carbonation) 507.1 (after carbonation)
dry weight (g)	498.6	499.3
wet weight (g)	538.3	538.6
density (kg/m^3)	1160.0	1202.3
Water absorption rate (%)	7.96	7.87

4.1.2 Microwave treatment combined with mechanical treatment

4.1.2.1 Microwave treatment

The temperature peaked during this waiting period when the temperature reached the value of T=368.38°C. The heating profile of the microwave heated sample is presented in Figure 14.

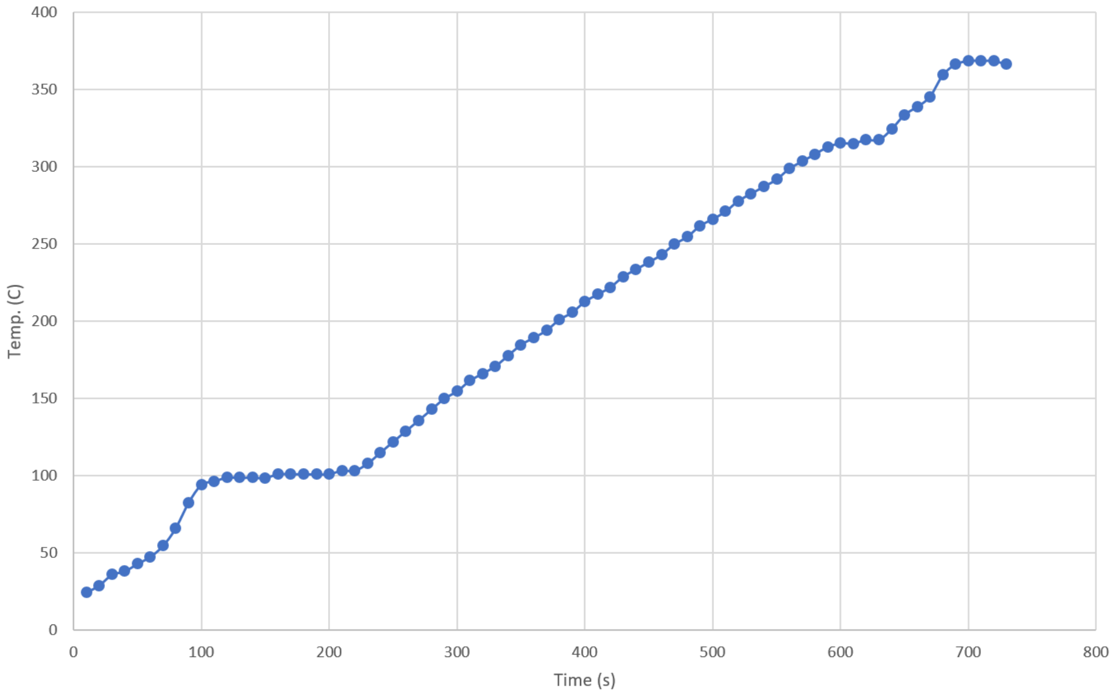


Figure 14. Heating profile of the RCA heated with a microwave of 4kW power intensity.

After allowing the sample to cool and after measuring its mass, the results revealed that the samples mass was reduced by 2.52% despite the fact that it had been oven-dried before the treatment. The lost mass can be assumed to be from moisture. A picture of the microwave sample right before removing it from the microwave oven is presented in Figure 15.

Figure 15. The sample inside the microwave oven after treatment.

4.1.2.4 Density and water absorption capacity

Finally, the sample was weighed again and its density was also measured before submerging the sample underwater for water absorption capacity measurements. The samples mass after mechanical treatment had reduced as expected, and because most of the reduced mass can be assumed to be from low-density mortar, its apparent density had increased. The lost mass during treatment can be assumed to be mostly adhered surface mortar, but inevitably some of the lost mass comes from powdered aggregate material. The changes in the mass, density and water absorption capacity of the sample are presented in Table 6.

Table 6. Properties before and after treatment

Property/stage	before treatment	after treatment
mass (g)	348.8	314.50
density (kg/m^3)	1160	1285
water absorption capacity (%)	7.96	10.08

4.1.3 Pozzolanic coating

4.1.3.1 Density

After the pozzolanic coating samples had been dried in a 100°C oven for 24 hours, they were sieved through a 2mm sieve to remove any powdered coating material that was not attached to the surface of the sample aggregates. After sieving the density of the samples was measured by weighing their mass in a 0.0002m^3 vessel. The results of the density tests illustrating the density differences between the samples are presented in Figure 16.

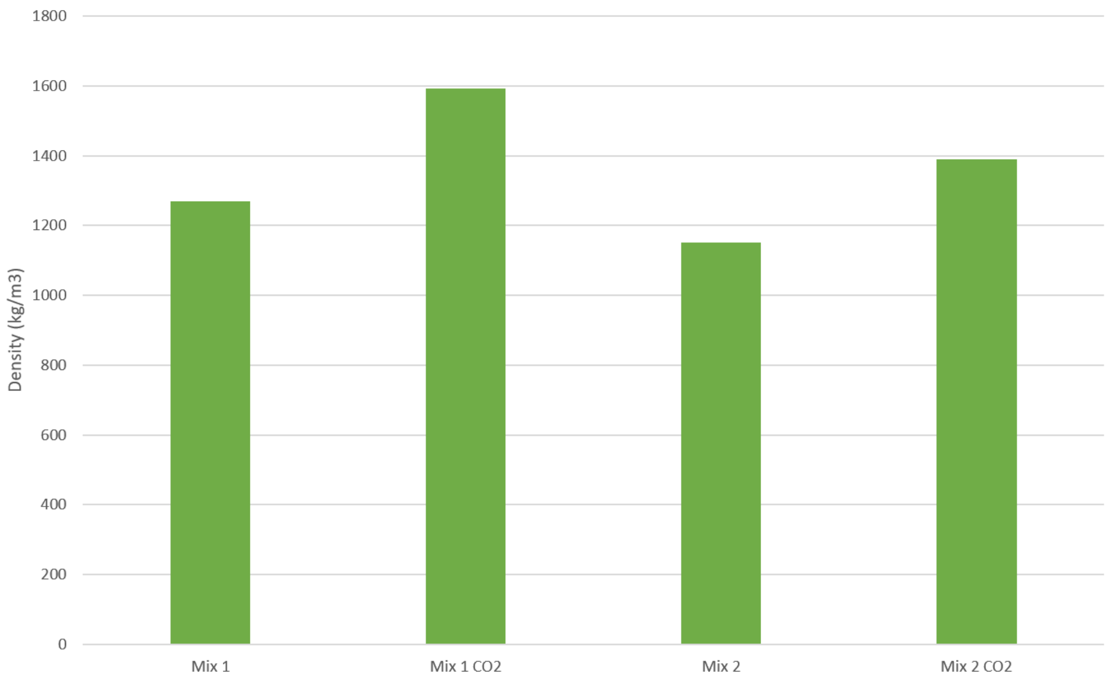


Figure 16. Density of pozzolanic coating samples after treatment.

As seen from the results, the variation between the samples was significant. The apparent density of the samples increased during the course of the treatment, except for Mix 2, where the density was determined to be slightly lower than before treatment. This might be caused by excessive low-density coating material on the surfaces of the aggregate material.

4.1.3.2 Water absorption capacity

Immediately after conducting the density measurements, the samples were immersed underwater for 24 hours and they were drained and wiped after the fact for wet weight quantification and water absorption capacity calculation. The results of the calculations are illustrated in Figure 17.

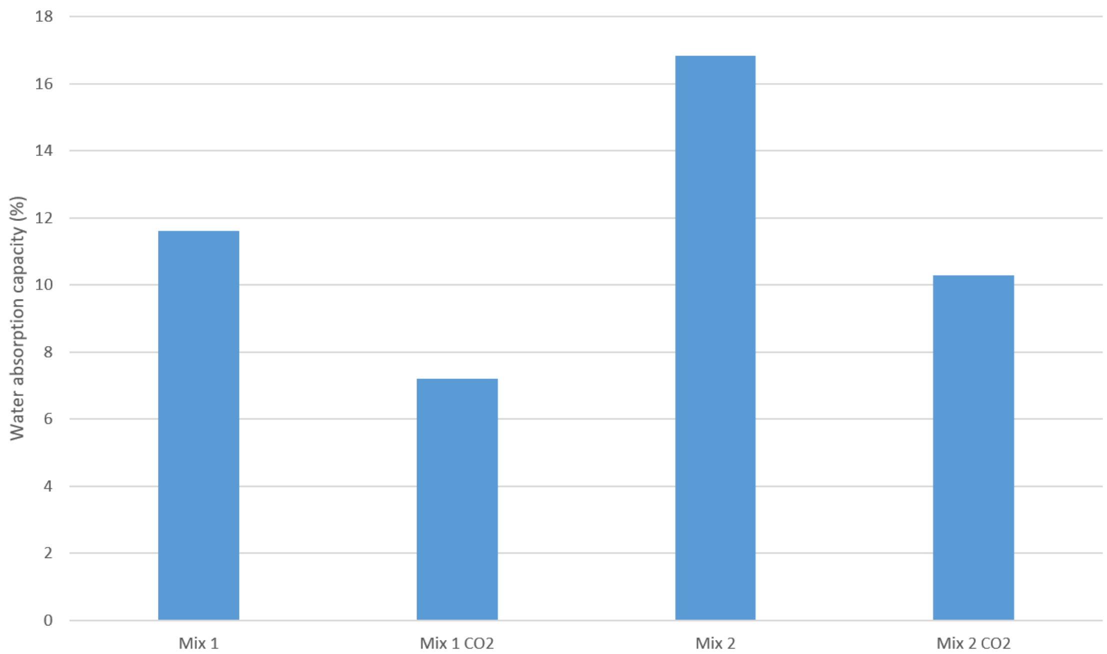


Figure 17. Differences in water absorption capacities between pozzolanic coating samples.

The results indicate that the water absorption capacity increases during pozzolanic coating treatment with pozzolanic slurries used in this experiment. The only sample with decreased water absorption capacity was sample called “Mix 1” that had been treated in a carbonation chamber for 24 hours after the coating.

4.1.4 Abrasion action mechanical treatment

After the sample was mechanically treated, its mass and density could be calculated immediately. Finally, after the sample had been submerged underwater for 24 hours, its wet weight after treatment and water absorption capacity could be calculated. The results of said calculation and the properties of the sample before and after treatment are presented in Table 7.

Table 7. Properties of the abrasion action sample before and after treatment.

Property:	Before treatment:	After treatment:
Mass (g)	500.10	479.23
Density (kg/m^3)	1160	1295
Water absorption capacity (%)	7.96	4.12

The results indicate that the abrasion action mechanical treatment is an effective way to increase the density and reduce the water absorption capacity of recycled concrete aggregates. The lost mass during treatment can be assumed to consist mostly of adhered mortar on the surface of the aggregates, but inevitably a portion of the lost mass originates from powdered aggregate material. More research should be done with various treatment times and other treatment parameters to find the optimal treatment circumstances.

4.1.5 Density measurements overview

The results of density measurements for all samples (including the untreated sample) of this study are presented in Figure 18.

The goal of the treatments was to increase the apparent density of the recycled concrete aggregates to enhance their strength properties. Excluding pozzolanic coating sample 3, the apparent density was increased with every treatment method. The highest density was measured for pozzolanic coating sample 2.

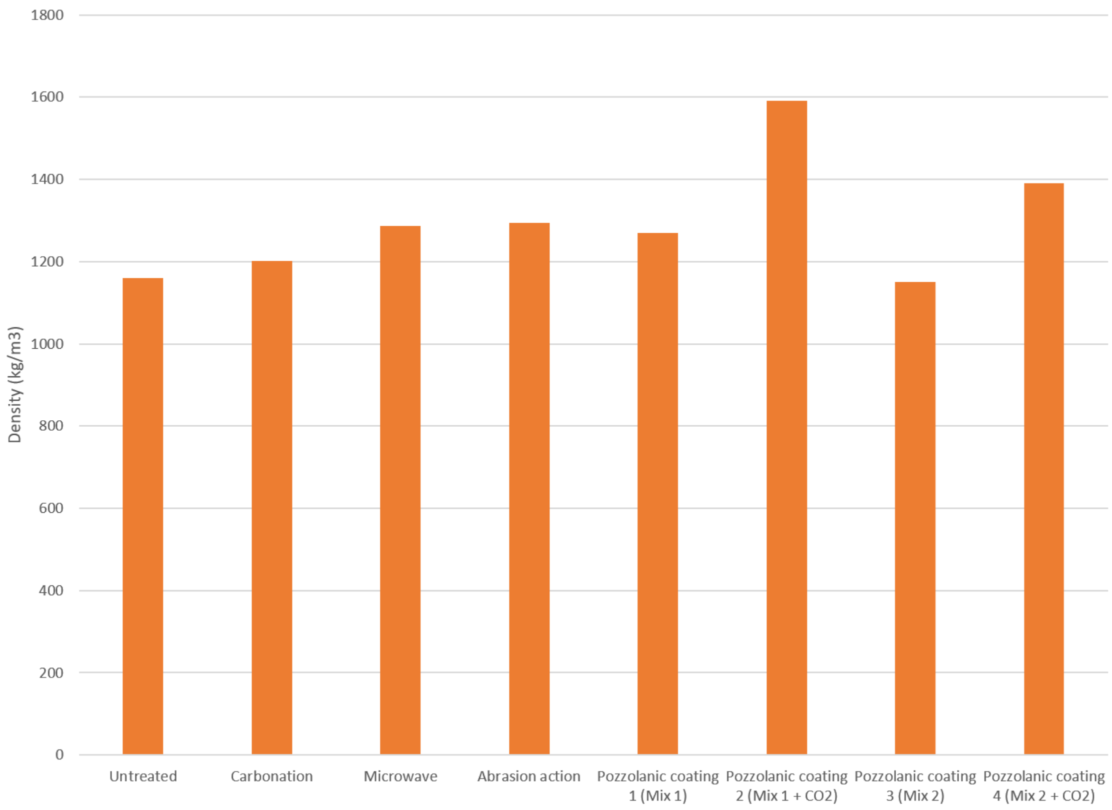


Figure 18. Density measurement results overview.

4.1.6 Water absorption capacity measurements overview

The results of water absorption capacity measurements for all samples (including the untreated sample) of this study are presented in Figure 19.

The goal of the treatments was to decrease the water absorption capacity of the recycled concrete aggregates to enhance their strength properties. The best results in this regard were achieved with abrasion action mechanical treatment, where the water absorption capacity was nearly halved. However, as seen from the results, the water absorption capacity increased during the treatments with four of the used treatment methods, especially with pozzolanic coating sample 1 and pozzolanic coating sample 3.

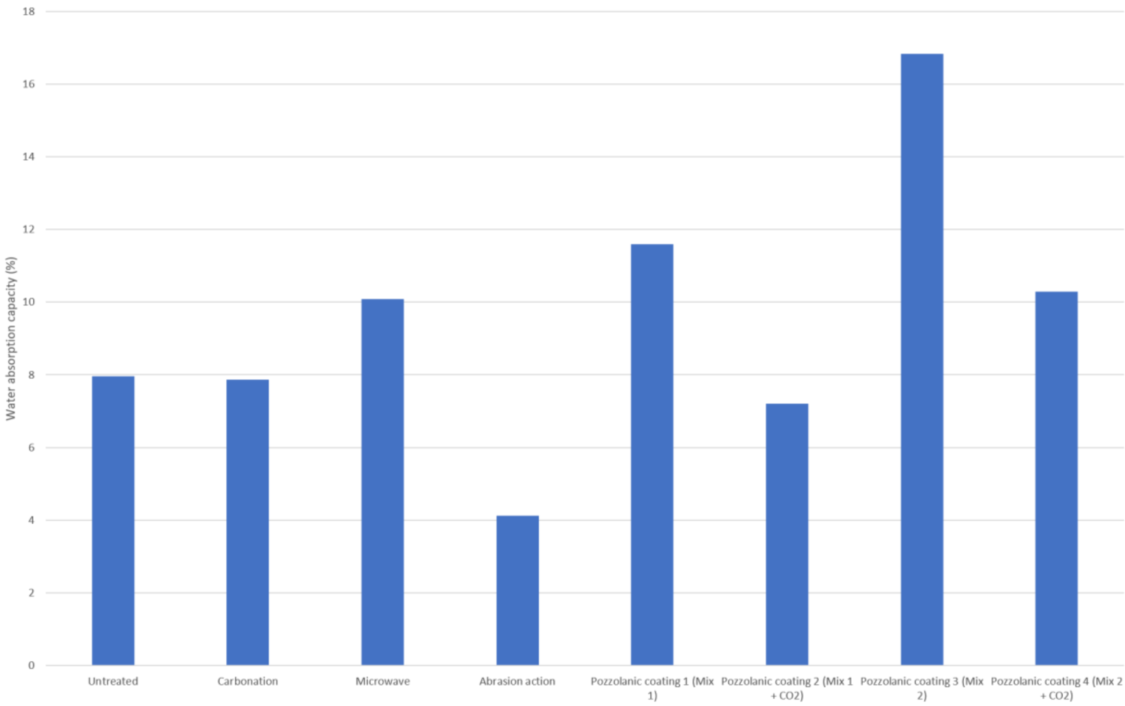


Figure 19. Water absorption capacity results overview.

4.2 Recycled concrete from treated aggregates

4.2.1 Concrete production

The goal of the final experiment for this thesis was to manufacture 125cm^3 concrete cubes using the treated recycled concrete aggregates and additionally one concrete cube using untreated RCA from the same material reservoir as the treated samples. Pictures of the treated recycle aggregates in addition to the untreated material are presented in Figure 20.

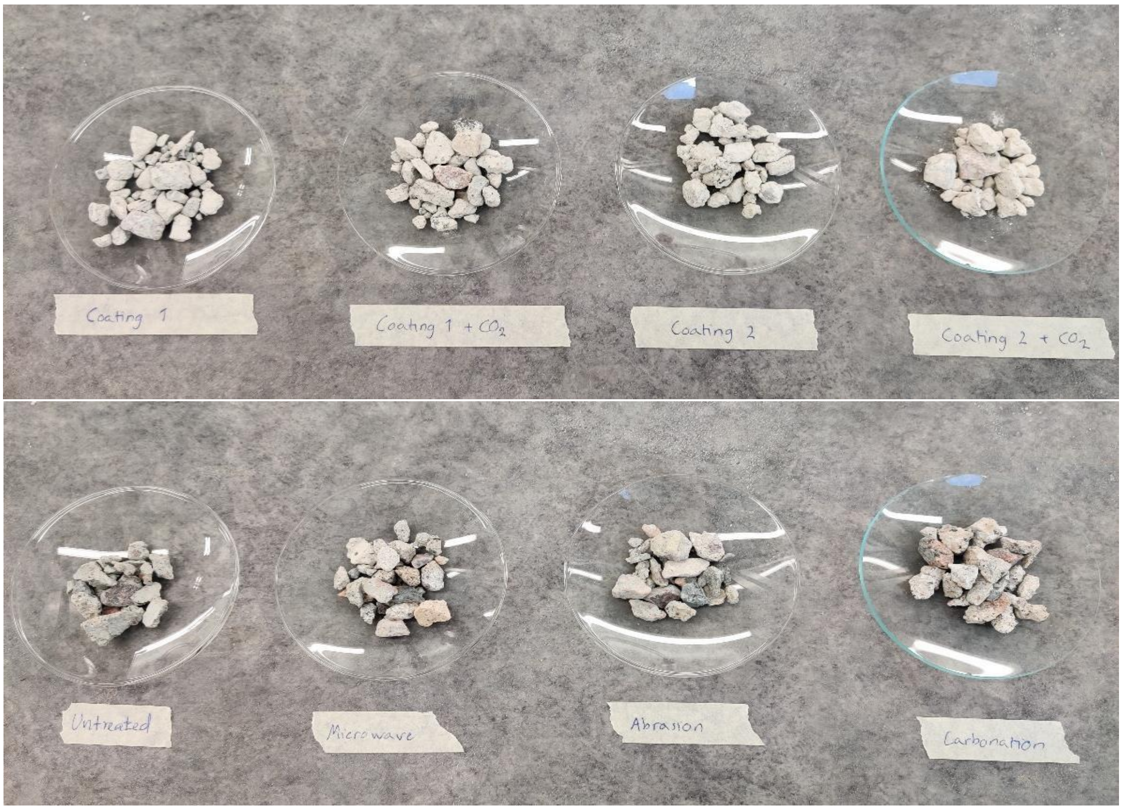


Figure 20. Samples of the RCA used in concrete making experiment.

All of the concrete specimen were made with identical mixture proportions. The binder used in the mixture consisted of powdered Na_2SiO_3 (10% of total amount) and slag (90% of total amount). Standard sand was used as the fine aggregate of the mixture (33% of total amount) and recycled concrete aggregate was used as the coarse aggregate of the mixture (67% of total amount). Filtered water was used as the liquid component in the mixing process. All of the specimen also followed an identical mixing procedure, which consisted of 30 seconds of mixing the dry components followed by additional 60 seconds of mixing once the liquid component had been introduced into the mixture.

Once the mixtures were ready they were poured into a 125cm^3 mould in which they were delivered to a humidity chamber to set and dry for 24 hours. Also smaller cubes were made from leftover mixture to be used for water absorption capacity testing. The small cubes were made into various sizes, since the volume of the specimen was not critical parameter for the water absorption capacity tests. A picture of the 125cm^3 mould containing one of the specimen is presented in Figure 21.

Figure 21. Concrete mould used in the experiment.

After the specimen had dried, they were removed from the mould and delivered back to the humidity chamber for seven days before continuing the experiment. A specimen made of pozzolanic coating sample 2 was broken during the removal of the cube, and thus there was no need to deliver it back to the humidity chamber. A picture of the broken specimen is presented in Figure 22.

Figure 22. Specimen that was broken during removal from the mould (Pozzolanic coating 2)

4.2.2 Hardened properties

4.2.2.1 Compressive strength

After the moulded cube specimen had been stored in a humidity chamber for seven days they were delivered to a separate facility for compressive strength testing. The test was performed by attaching the specimen into a compression testing machine and introducing force at a rate of 2.4 kN/s into the cube until it breaks down. Compressive strength is calculated with formula 4.

$$P = \frac{F}{A} \tag{4}$$

Where P is pressure, F is force in Newtons and A is the surface area in cm^3.

The results of the compressive strength tests are presented in Figure 23. The specimen called pozzolanic coating 4 is the same as the pozzolanic coating sample 3 combined with CO_2 curing.

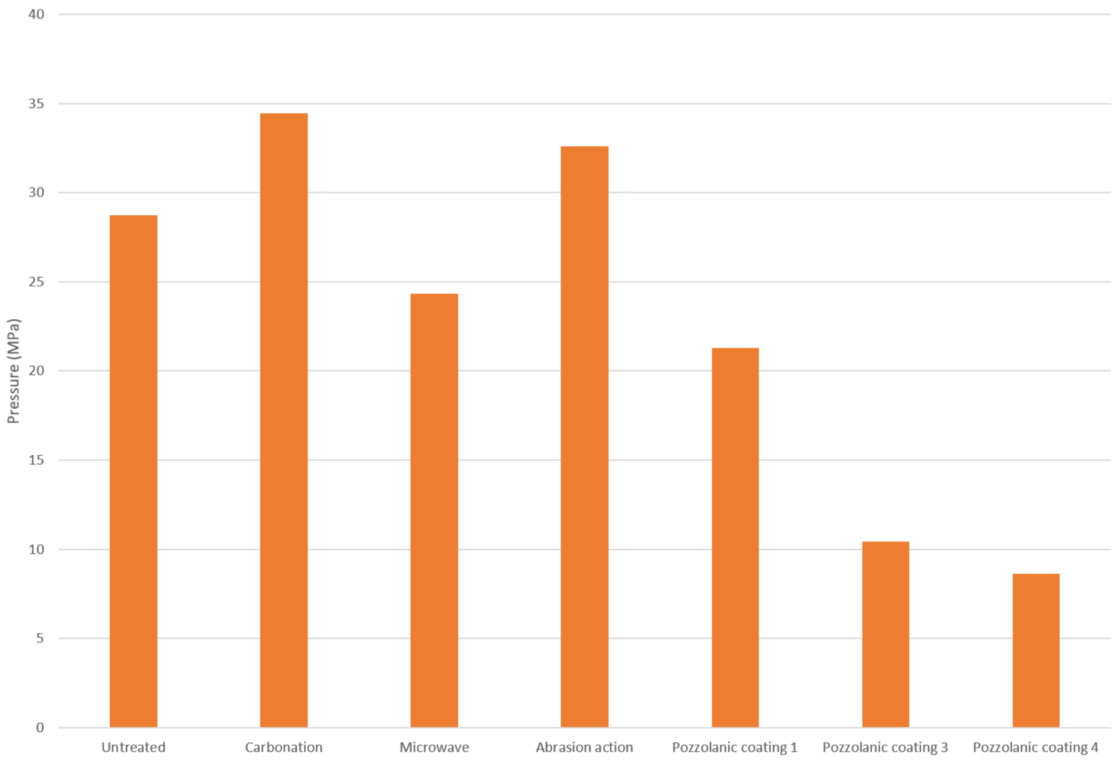


Figure 23. Compressive strength test results.

As can be seen from the results chart, only the specimen cubes made from carbonated RCA sample and the abrasion action RCA sample performed better than the untreated control sample. This indicates that using standard CO_2 curing increases the strength properties of the RCA even with relatively short treatment times. Also the abrasion action mechanical treatment shows promising results in enhancing the compressive strength capacity of the material. Unexpectedly, the results were much better than with microwave treatment specimen, which had also undergone abrasion action treatment, which indicates that more research needs to be made on the combination of said treatment methods. The results contradict the results of research made by Akbarnezhad et. al (2011) where microwave beneficiation treatment increased the compressive strength properties of recycled concrete aggregates, but different microwave oven and treatment parameters were used in that research experiment in addition to different type of sample material..

In addition to this, the cubes made with pozzolanic coating RCA samples had the poorest performance overall. This contradicts the research results of Li et. al (2009) and Zhihui et. al. (2013) where pozzolanic coating was found to greatly increase the compressive strength properties of recycled aggregates. This can be due to various reasons, but most likely the differences in results are caused by different mixing methods and components used for the pozzolanic slurry. Thus it can be deduced that using the same materials and proportions during the pozzolanic coating treatment that were used in this experiment is not a viable way to enhance the strength properties of recycled concrete aggregates. More research needs to be done to find more suitable mixing proportions and also more research must be made to decide if combining pozzolanic coating treatment with CO_2 curing can be an effective combination for enhancing the strength properties of the aggregates even further, since the results in this experiment indicate that, the combination of said treatments decreases the compressive strength of the recycled aggregate concrete.

4.2.2.2 Water absorption capacity

After the concrete cubes made of leftover mixture material had been stored in a humidity chamber for seven days, their water absorption capacity was tested following the same testing protocol as with the RCA samples. The results of the water absorption capacity tests are shown in Figure 24.

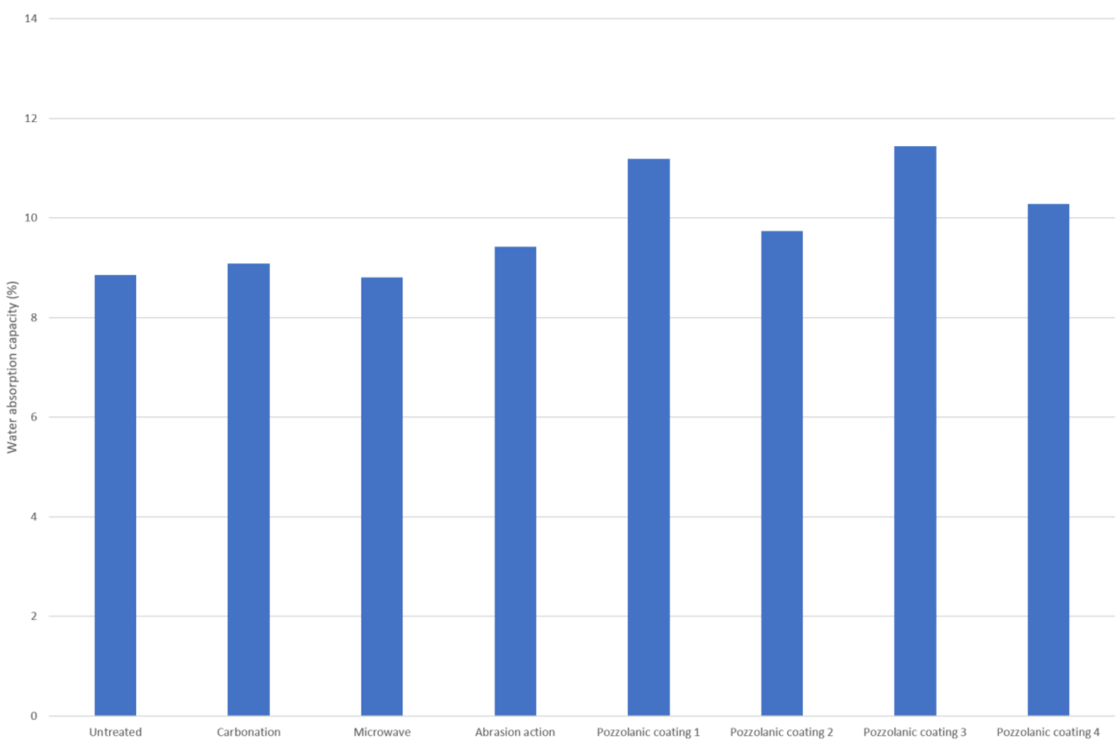


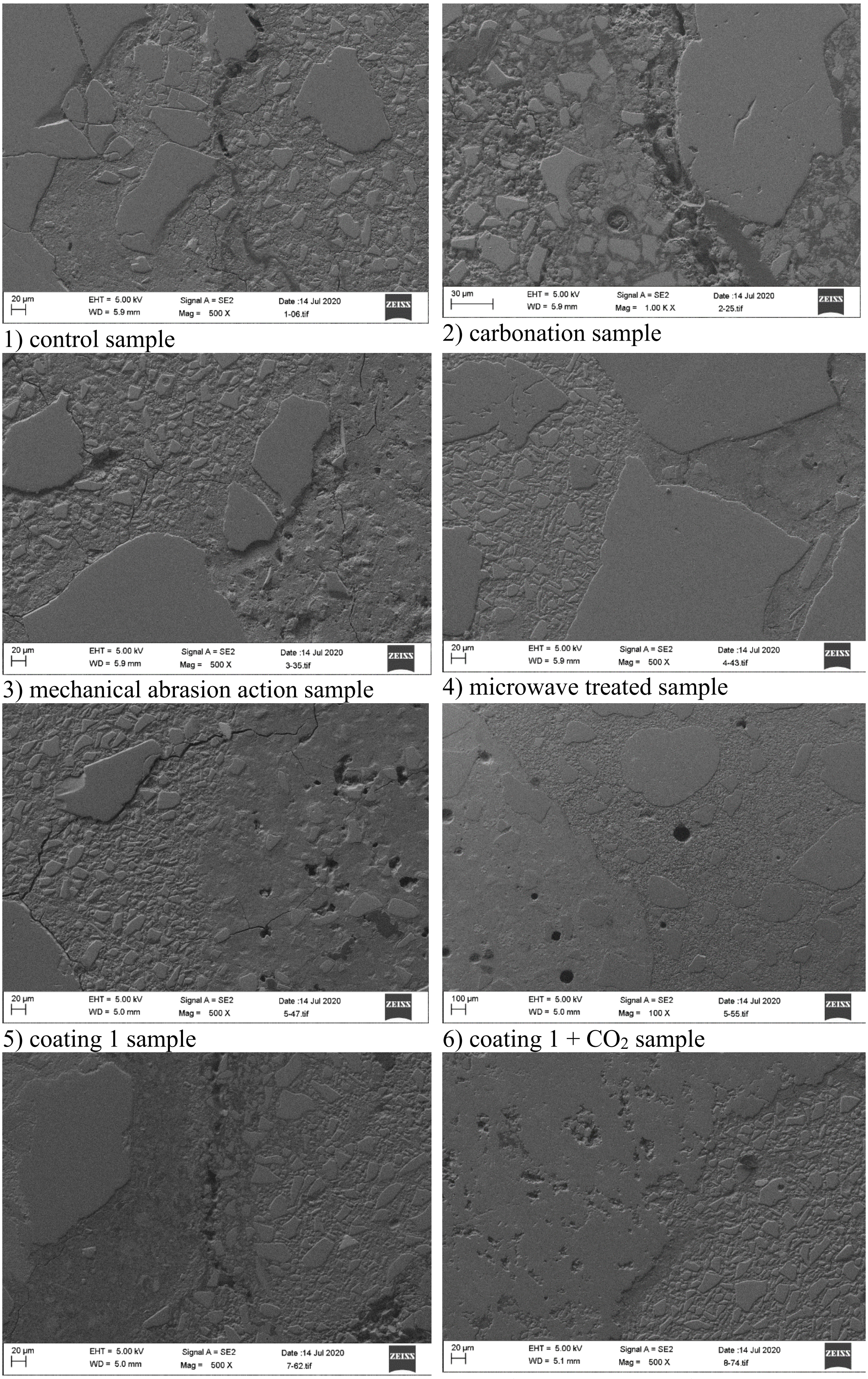
Figure 24. Water absorption capacity test results for concrete cubes.

As seen from the results, only the concrete made with microwave treated RCA had a marginally lower water absorption capacity than the specimen made of untreated RCA. The concrete samples made with pozzolanic coated RCA had the poorest results out of all of the specimen, but it seems that using carbonation treatment in addition to pozzolanic coating treatment yields better results by decreasing the water absorption capacity. This is consistent with research made by Shi et. al (2018) concluded that using a combination of pozzolanic coating treatment and CO_2 curing reduces water absorption by 21-26%. However, more research needs to be done to optimise both the composition of the pozzolanic slurry and also the treatment parameters of the carbon dioxide curing for best possible results.

Also an interesting aspect can be seen from the results when comparing microwave treated concrete and concrete containing only mechanically treated RCA is that the microwave treated concrete yielded the best results for the water absorption capacity tests even though the compressive strength test results were better for the mechanically treated concrete sample.

4.2.2.3 Microstructural studies

Scanning electron microscopy (SEM) was utilised to study the microstructure of the manufactured concrete samples to see if the visual outlook of the material correlated with the previous physical property measurements. The SEM-samples originated from the broken fragments that had been acquired from the compressive strength measurements and before SEM they were impregnated in epoxy and polished. The SEM-images of the samples are presented in Figure 25. The images show the interfacial transition zones (ITZ) between the aggregate, adhered mortar and new alkali-activated cement material in the sample.



1) control sample

2) carbonation sample

3) mechanical abrasion action sample

4) microwave treated sample

5) coating 1 sample

6) coating 1 + CO_2 sample

7) coating 2 sample

8) coating 2 + CO_2 sample

Figure 25. SEM-images of manufactured concrete specimen.

As seen in Figure 25 the ITZ in the control sample are clearly separated from the newly formed mortar and there is also a clear line between the old adhered mortar and new mortar. Carbonation sample clearly shows less pores, has less micro-cracks on the ITZ of aggregate and new mortar and seems overall denser, but has more cracks in the cement matrix. It can be speculated that the cracks are caused by the CO_2-curing treatment itself due to the high density of the material. That would also partly explain the higher water absorption capacity compared to the control sample.

Even though at least some of the old adhered mortar was removed during the mechanical abrasion action treatment, the SEM-image shows that some of said mortar still remains around the aggregates. Nevertheless, the amount of pores in the sample seem to be quite scarce and existing cracks are mostly located within the cement matrix instead of the aggregates.

In the image from the microwave treated sample it seems that the aggregate material and surrounding adhered mortar material have been merged due to high heat, but a clear ITZ can still be seen between the aggregate and old mortar. Some of the aggregates had also cracked severely, but those aggregates can be assumed to be of different, less heat resistant material.

All of the pozzolanic coating samples showed similar attributes in their respective SEM-images. The coated area was clearly visible and it contained a lot of pores and cracks, even severely eroded areas especially in the non-carbonated samples. This indicates that the slag-based coating material is physically weaker compared to the alkali-activated cement material used in all of the concrete specimen. However, the carbonated coating samples showed fewer cracks and pores in the coated area that maybe due to the carbonation reaction. In sample 6) the carbonation reaction seemed to be especially effective.

These results correlate well with the results of the compressive strength test and the water absorption capacity test that was performed on the manufactured concrete specimen. The mechanical abrasion action sample had the most pristine microstructure out of all of the samples while the coating samples had the least. Nevertheless, more research should be done on the pozzolanic coating treatment and alter the composition of the coating material to be more similar with the binding material of the concrete.

5 CONCLUSIONS

In this thesis, the most commonly used treatment methods for recycled concrete aggregates in scientific research were identified based on literature from the past 10-15 years and five types of said treatments were experimented on in laboratory conditions. The main theme of the experimental part of this thesis was to determine the most effective treatment method by measuring various parameters from the treated samples as well as an untreated control sample. The final experimental phase of this thesis was to manufacture concrete from the same treated aggregates and to quantitatively determine the most important physical properties of the created concrete specimen.

The five chosen treatment methods that were observed in this thesis were CO_2 curing, pozzolanic coating treatment, pozzolanic coating treatment combined with CO_2 curing, mechanical abrasion action treatment and microwave treatment combined with mechanical abrasion action treatment. Treatment methods that were introduced during the literature review section of this thesis, but were excluded from the experimental part included high-voltage beneficiation method, polymer treatment method, hybrid treatment method, thermal beneficiation and mechanical treatment methods other than abrasion action method.

The most important physical properties that were measured from the treated recycled concrete aggregate samples were apparent density and water absorption capacity. In addition to this, compressive strength capacity and porosity were measured from the concrete samples made from the treated RCA samples and an untreated sample.

Considering only enhancing the physical properties of treated RCA samples section of the research, best results overall were received with the mechanical abrasion action treatment. The water absorption capacity of this particular sample was almost halved compared to the control sample, and this was the best result overall in the water absorption measurements. The apparent density of the sample also increased compared to the control sample, but the result was inferior to some of the pozzolanic coating samples. Nevertheless, it can be assumed that the treatment was effective in removing low-density mortar material from the surface of the aggregates even with such a short treatment time and relatively low rotational speed of the used machinery.

When comparing the results of the compressive strength test which was performed on the produced concrete cubes, most of the sample cubes performed poorly compared to the control sample cube. With that said, the carbonation and mechanical abrasion action samples had significantly higher compressive strength capacity than the control sample and in that light they should considered to be used in recycled concrete manufacturing. More research should be made with these treatment methods both separately and in tandem to see if their benefits complement each other. Unexpectedly though, both samples had higher water absorption capacity compared to the control sample, but that was true with all samples except with the microwave treated sample cube, which had marginally lower water absorption capacity than the control sample.

The SEM-images that were taken from the manufactured concrete samples supported the results that had been received from the compressive strength test and water absorption capacity test. The most interesting findings were that CO_2-might fortify the cracking effect within the adhered mortar if the material is initially relatively dense already, and that the relative structural weakness of the coating material used in pozzolanic coating treatment compared to the used binding material causes higher the cracking of the coating material and might also be responsible for the higher porosity of the cement matrix. So it can be assumed that using slag-based coating material is not an effective way to enhance the physical properties of recycled concrete if the binding material is alkali-activated.

Overall, the results of this study indicate that mechanical abrasion action treatment is an effective way to enhance the physical properties of recycled concrete. CO_2-curing also yielded good results since the physical properties of the sample material were enhanced significantly. Due to its simple and time-effective treatment process, mechanical abrasion action treatment should be studied further in the future, especially in tandem with CO_2-curing in case the beneficial effects of the treatment methods stack and yield even better results together.

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